Land Surface Rehabilitation Research in Antarctica

KEVIN KIERNAN AND ANNE MCCONNELL

School of Geography and Environmental Studies,
University of Tasmania, Tasmania 7005

Kiernan, K. and McConnell, A. (2001). Land surface rehabilitation research in Antarctica. *Proceedings of the Linnean Society of New South Wales* **123**, 101-118.

Ice-free ground surfaces in the Australian Antarctic Territory are sensitive to damage by artificial disturbance. Natural processes appear generally inadequate to heal the resulting scars over human time scales and substantial ongoing environmental impacts may accrue where melting of subsurface permafrost is triggered. Studies of some rehabilitation projects at sites where significant ground disturbance had been caused during geoscientific research indicate that although specific site conditions are critical to the approach taken, environmental harm can be reduced provided maximum advantage is taken of the opportunities to minimise and manage impact at each of the project design, environmental review, site selection, operational and rehabilitation phases. These sites provide a useful analogy for larger disturbances caused by infrastructure development.

Manuscript received 1 August 2001, accepted for publication 21 November 2001.

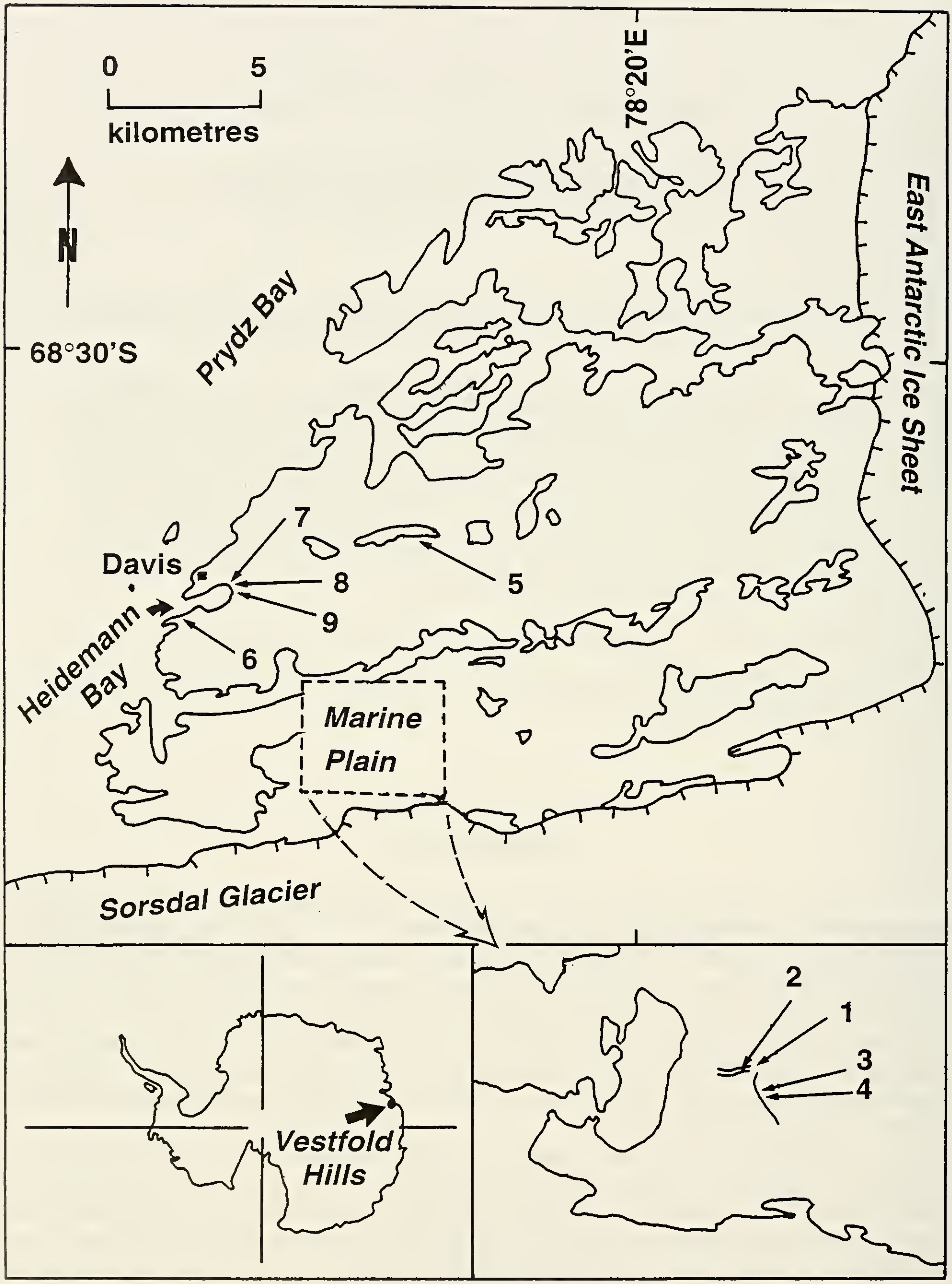
KEYWORDS: Antarctica, Vestfold Hills, environmental impact, geoenvironment, geoconservation, land rehabilitation.

INTRODUCTION

Ice-free land surfaces in the Australian Antarctic Territory can be particularly susceptible to environmental damage (Schofield 1972, Parker and Howard 1977). Anthropogenic disturbance resulting from some research and engineering activities can produce scars that take a very long time to heal (Campbell and Claridge 1987). Where a permafrost layer becomes exposed, meltwater discharge, severe channelisation, erosion and slope instability may result (French 1976, Burgess et al. 1992). Present expertise and experience in Antarctic land surface rehabilitation is very limited and the lack of significant vegetation deprives land managers of an important rehabilitation tool generally available elsewhere (McVee 1973).

As a party to the Protocol on Environmental Protection to the Antarctic Treaty or "Madrid Protocol" (Antarctic Treaty Consultative Parties 1992), Australia has legal obligations to protect the Antarctic environment. There is also a public expectation that environmental protection in Antarctica be very strict, although this has not always been the reality and a legacy of scars already exists in some areas. Apart from infrastructure development, the most obvious potential for scarring of the landscape arises from geoscientific research that involves excavation to allow investigation and sampling of subsurface materials. The perceived potential for environmental harm contributes to occasional advocacy that geoscientific research in Antarctica should be restricted (Graham 1997).

Figure 1. Localities mentioned in text. The numbers indicate localities referred to in Table 2.



Recent research in the Vestfold Hills has revealed that geoscientific research accounts for nearly half the recorded sites of persistent human impact on the physical environment outside Davis Station limits (Fig. 1). Comparisons between rehabilitated sites and others where little if any rehabilitation had been attempted revealed that natural processes alone are generally insufficient to heal the damage. This paper details the specific environmental protection and remediation strategies that facilitated the reduction in environmental harm observed at the rehabilitated sites reported upon in that study (Kiernan and McConnell 2001). We describe and evaluate planning and site management designed to reduce environmental impacts, and surface rehabilitation methods employed. We compare site conditions immediately subsequent to the rehabilitation work with the results of site monitoring undertaken just under four years later.

Physical impact of geoscientific excavations

Ice-free Antarctic land surfaces are characterised by a lack of significant vegetation, a relative scarcity of water, a very slow rate of soil material movement, a ground surface that comprises unconsolidated material that is commonly overlain by a desert pavement of lag gravels and coarse sands, and the presence of subsurface permafrost (Campbell and Claridge 1987). Excavation inevitably involves disturbance of the natural stratigraphy, especially if waste material is replaced in the pit. Unnatural change to surface contours, at whatever scale, by definition damages the natural geomorphology. Natural soil properties may be compromised through soils adjacent to an excavation becoming contaminated by spoil, especially if it is redistributed by the wind (Campbell and Claridge 1987). Some research requires that the pristine condition of the Antarctic environment is maintained, for example understanding the accumulation of soil nitrate from atmospheric circulation, but local soil contamination has been demonstrated (Campbell and Claridge 1987, Claridge et al. 1995).

Excavation can also interfere with ongoing natural processes, as when removal of a desert pavement lag exposes underlying finer material to wind erosion. Any failure to adequately reconsolidate spoil replaced in a pit may result in progressive settling that ultimately creates a depression. Alternatively, a difference in bulk density relative to the undisturbed material surrounding the pit may leave fill prone to differential permafrost development. Impacts on aesthetic values may include changes to form, line, colour and texture of a landscape (United States Forest Service 1974, Laurie 1975) and such changes may be particularly evident in open Antarctic environments where masking vegetation is absent.

Some researchers may consider backfilling of research excavations to achieve little because the disturbance is permanent and difficult to conceal (Campbell and Claridge 1987). The permanent impact of excavation upon the natural stratigraphy is impossible to undo in any practical or useful way even if harm might be reduced were material from different strata stockpiled separately and replaced in the order in which it was originally encountered (Campbell et al. 1993). However, other potential adverse effects including long term changes to natural processes may be minimised if appropriate techniques are developed. Some geomorphological and visual impacts may be reduced by efforts to reproduce the original shape, texture and form of the ground. Contamination of soils adjacent to pits can be minimised by stockpiling spoil on cover sheets or placing it in bags so it is not left exposed to wind.

Campbell et al. (1993) have shown that some shallow excavations and vehicular tracks can persist for more than 30 years, but that some types of impact can recover more quickly where there are repeated freeze-thaw cycles, and to a lesser extent wind action. Improved understanding of the degree of repair that is desirable and achievable is important in order to reduce environmental harm caused by research. Research excavations can also provide a small scale analogy for the larger disturbances caused by the provision of infrastructure for science, tourism or other purposes, and the information obtained may help inform planning and remediation of larger projects.

Table 1. Assessment criteria for rapid visual evaluation of terrestrial environmental impacts, and scoring system. Items A-K are from Campbell et al. (1993); items L-P are from Kiernan and McConnell (2001).

Impact assessment criteria	*Severity and extent of impacts (class)* 1	2	3	4
A. Disturbed surface stones	none visible 0	few <10	many 10-25	abundant >25
B. Stone impressions	none visible	just visible	distinct	fresh
C. Boot imprints	none visible	just visible	distinct	fresh
D. Visibly disturbed area	<5 m^2	5-10 m^2	20-100 m^2	>100 m^2
E. Colour difference (Munsell units)	none visible	weak contrast	moderate contrast	strong contrast
F. Other surface impressions (eg. equipment)	none visible	weakly visible	distinct	very fresh
G. Walking routes	not visible	weakly defined	moderately defined	strongly defined
H. Foreign objects	none visible 0	few <10	some 10-25	many >25
I. Fuel spills	none visible	faintly distinguished	visible	very obviou
J. Biological disturbance	none visible	<1 m^2	1-5 m^2	>5 m^2
K. Cumulative impact (scale 1-10)	disturbance not visible	weakly distinguished	clearly visible disturbance	disturbed & very obvious
L. Stratigraphic disturbance	negligible	within on unit	within two units	multiple units
M. Morphological or texture change	negligible	just evident	moderate very change	obvious
N. Rock cairns	none	rare or small	moderately common or large	very common & obvious
O. Paint marks	none	rare or small	moderately obvious	very obvious
P. Other marks (eg. stakes)	none	rare or small	moderately obvious	very obvious

GENERAL METHODOLOGY

In 1996 we became involved in a geoscientific research program in the Vestfold Hills that included excavation of a number of small soil investigation pits on moraines and larger excavations at Marine Plain and Heidemann Bay (Fig. 1). The purpose of the Marine Plain excavations was to investigate sediments and ground ice conditions, and to evaluate evidence for reported soil development. The Heidemann Bay excavation involved re-evaluation of evidence for a claimed phase of climatic warming (Hirvas et al. 1993) that, if correct, had major implications for understanding the evolution of Antarctic environments and global climate change.

The excavations were undertaken only after prior environmental evaluations and approval by the Australian Antarctic Division, and were planned to minimise adverse impacts consistent with achieving the scientific goals. Concerted efforts were made to achieve a high level of ground surface rehabilitation. The system developed by Campbell et al. (1993) was employed to record rapid visual estimates of the remaining impacts, supplemented by some additional criteria (Kiernan and McConnell 2001) including the use of Standard Rock Colour Charts (Goddard et al. 1948) (Tables 1 and 2). Photo-monitoring was initiated and record made of any physical evidence suggestive of artificially accelerated melting of permafrost. This assessment process was repeated just under four years later. The condition of some sites not effectively rehabilitated by previous researchers prior to advent of the Madrid Protocol was also recorded on both occasions to permit assessment of the relative efficacy of deliberate rehabilitation compared to natural processes that might effect repair (Table 2).

REHABILITATION TECHNIQUES AND RESULTS

Marine Plain

Marine Plain is floored by a veneer of glacial sediment over Pliocene marine diatomite. The rocks are subject to intense salt weathering in this very arid environment. Permafrost occurs below ~1 m depth and the local landforms have evolved due to very slow progressive melting of ground ice (Kiernan et al. 1999). Terrain produced by this process is known as periglacial thermokarst because the resulting depressions give the topography an appearance similar to that of conventional limestone karst. Significant geohazards associated with thermokarst are well documented from the northern hemisphere and include the risk of accelerated subsidence, slumping and the discharge of meltwater to the surface where disturbance of the seasonally-thawed "active layer" so modifies the thermal condition of deeper permafrost as to accelerate its melting (French 1976). Environmental issues at Marine Plain also include the sensitivity of the ground surface to trampling. A thin crust, possibly gypsum, occurs over the loose, powdery surface horizons of the diatomite, and this crust is crushed by foot-fall, in the same manner as very thin flowstone in a limestone cave. This releases a plume of diatomite dust which in windy conditions facilitates soil contamination risks of the kind alluded to by Campbell and Claridge (1982) and also leaves a persistent sharply-defined, colour-contrasting footprint. Some observed footprints appeared to have persisted since at least the previous summer and hence were at least a year old. Un-rehabilitated pits monitored in January 1997 and December 2000 showed little evidence of healing by natural processes (Table 2, site 1) (Kiernan and McConnell 2001).

Table 2. Impact assessment (in 1997 & 2000) of some excavation sites, including some data from Kiernan and mcConnell (in press). See Table 1 for criteria and scoring system. No data = nd.

assessment criteria site	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Marine Plain																
1a	4	4	4	3	nd	4	3	3	1	1	4	2	4	1	1	4
1b	4	4	2	3	nd	4	2	3	1	1	3	2	4	1	1	4
2a	4	2	1	4		4	2	1	1	1	4	3	4	1	1	1
2b	4	4	1	3	nd	4	2	2	1	1	4	3	4	1	1	1
2c	4	2	1	3		4	2	1	1	1	4	3	4	1	1	1
3a	4	2	2	3	3	2	3	1	1	1	3	3	2	1	1	1
3b	1	1	1	1	1	1	1	1	1	1	3	3	2	1	1	1
4a	3	2	2	3	nd	2	2	1	1	1	2	3	1	1	1	1
4b	1	1	1	1	nd	1	1	1	1	1	1	3	1	1	1	1
Heidenmann Valley																
5a	3	3	1	2	nd	4	1	1	1	1	4	2	4	1	1	1
5b	3	3	1	2	nd	4	1	1	1	1	4	2	4	1	1	1
6a	3	3	3	2	nd	4	1	1	1	1	4	2	4	1	1	1
6b	3	3	3	2	nd	4	1	1	1	1	4	2	4	1	1	1
7a	3	1	1	3	1	2	2	1	1	1	1	1	1	1	1	1
7b	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8a	2	1	2	1	1	1	2	1	1	1	1	2	1	1	1	1
8b	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
9a	4	2	1	4	1-2	2	2	1	1	1	2	4	1	1	1	1
9b	1	1	1	1	1	1	1	1	1	1	1	4	1	1	1	1

Sites:
Marine Plain:

1= small un-rehabilitated pits believed to have been excavated in 1995-96 (a) condition in January 1997, (b) in December 2000.
2= Big Ditch site (a) un-rehabilitated condition prior to re-distrubance in 1997, (b) immediately after rehabilitation attempt in January 1997, (c) in December 2000.
3= 1997 scarp trench (a) immediately after rehabilitation in March 1997, (b) in December 2000.
4= 1997 pit above main trench (a) immediately after rehabilitation in January 1997, (b) in December 2000.

Heidemann Valley:

5= old un-rehabilitated soil pit on Stinear Moraine (a) in March 1997, (b) in December 2000.
6= old un-rehabilitated soil pit on moraine on south side of Heidemann Bay (a) in March 1997, (b) in December 2000.
7= Section of previously un-rehabilitated bull-dozed track re-used in 1997 (a) immediately after rehabilitation attempt in March 1997, (b) in December 2000.
8= Cross-country route between old bulldozed track and trench site (a) immediately after rehabilitation in March 1997, (b) in December 2000.
9= 1997 trench (a) immediately after rehabilitation in March 1997, (b) in December 2000.

Big Ditch (Table 2, site 2)

Big Ditch is a natural elongate depression across northern Marine Plain. A substantial excavation had already been undertaken on the depression margin by earlier researchers, hence re-excavation here avoided creation of a new disturbance, and also provided an opportunity to experiment with repair of a site where a significant impact had already been caused with no effective rehabilitation. The earlier disturbance had involved a cut ~5 m wide, 2 m high and penetrating ~5 m into the side of a natural scarp. Initial observations in January 1997 revealed a bulge in the foot of the old excavated face, and a deposit of fine sediment and surface salt that extended downslope, suggesting accelerated permafrost melting had resulted from the original disturbance. The 1997 research required cleaning-back the previously-excavated face by ~10 cm to reveal a vertical section 50 cm wide and 135 cm high. Excavation, sampling and rehabilitation were completed in one day.

It proved impracticable to do more than seek to ensure our re-disturbance was no more visually evident than was the much larger artificial face and hole in which it was sited. The original large excavation could not be filled and the overall slope restored because the spoil from the earlier excavation had spilled downslope and been redistributed by wind and meltwater such that little could be retrieved without risking significant additional disturbance. An attempt was made to reduce visual impact by using the very small volume of spoil that could be retrieved to mimic the natural slopes to either side. Efforts were made to reproduce the slope angle, colour and texture of the face of the earlier excavation, itself very conspicuously artificial. Old discarded scraps of latex and hessian were also removed. Some larger rocks retrieved from the earlier spoil were distributed along the top of the face to mimic the adjacent pattern of glacial boulders spilling onto the upper scarp.

Immediately after rehabilitation on 24 January 1997 the new disturbance was difficult to distinguish from the earlier excavation (Fig. 2a). The newly-disturbed surface was a mixture of unweathered sediments from various depths. The colour contrast between the newly disturbed and previously disturbed surfaces was moderate at two Munsell units, but this did not reflect the real visual impact of the original excavation on the broader landscape. Because the depression in the active layer caused by the earlier excavation was not filled, the potential remained for continued permafrost melting.

When the site was monitored on 11 December 2000 some further movement of the lower part of the face by solifluction was evident. Discolouration of downslope areas by salt and fine sediment was more pronounced than in 1997 (Fig. 2b). These observations were interpreted as indicating that thawing of the permafrost had been accelerated by renewed disturbance of the active layer. Hence, the structural and cosmetic rehabilitation attempted had not been sufficient to redress the effects of the re-disturbance superimposed upon the original un-rehabilitated excavation.

Scarp trench (site 3)

A trench 22 m long and 30-40 cm wide with a series of benches along its length was excavated down the face of a scarp 9.5 m high (Figs. 3a and 3b). The area disturbed was minimised by restricting pedestrian access to the line of the trench. Placing the large volume of spoil on a ground sheet to reduce the spread of lighter coloured material was not practical on the steep slope, and additional degradation was judged likely if spoil was carried from the top to the bottom and then vice versa. For these reasons, spoil was placed to one side so that sediments of different kinds would not become mixed in a pile at the foot of the slope, and so the broad composition and colour of the material excavated could be replaced as closely as possible to its original position. Small calibre scree was stockpiled separately and larger rocks were also segregated. Excavation, sampling and rehabilitation were accomplished within two days.

Figure 2. Big Ditch site (site 2): (a) in January 1997, immediately after disturbance and rehabilitation of the old excavation site; and (b) in December 2000, showing fine sediment and salt deposited by meltwater still being released from the permafrost.

Figure 2a.

Figure 2b.

An attempt was made to minimise alteration of the natural geomorphology by seeking to (1) minimise changes to the insulating properties of the disturbed active layer that might otherwise trigger permafrost melting and slope instability; (2) mimic an old lake shoreline on the slope, and (3) mimic the natural distribution of scree. Only material that had been removed from the excavation was used to refill the trench. The natural morphology and surface rock distribution were reproduced as closely as possible with respect to (1) swathes of fines that extended down the slope, (2) a distinct break of slope above a clay zone; and (3) a steep slope facet in rocky upper areas of the scarp. An attempt was also made to restore the aesthetic values by identifying and focussing upon what were judged to be the dominant site-specific visual elements, namely (1) the natural profiles of the lower slope, both longitudinal and lateral; (2) the bouldery texture of the top of the slope; (3) the surface colour pattern, involving lighter-coloured sediment upslope and a distinct darker band downslope; (4) the presence of cobbles lower down the slope; and (5) the presence of gravelly scree that commenced at half height on the slope.

During rehabilitation each bench within the trench was used as a foundation upon which returned spoil could be placed, to ensure that any later settling would occur in small localised units rather than being sequentially transmitted down the full length of the trench. Larger rocks were placed towards the outer edge of each bench to retain fine material and the fill was consolidated on a bench-by-bench basis and manually compacted. Restoration was undertaken from the top downwards rather than from the bottom upwards, so that each bench had to be made stable in its own right. The retained scree was utilised in an attempt to mimic the natural veneer of lag gravels in an effort to obtain as natural a surface texture and appearance as possible. Replacement of the original surface clasts weathered side up helped further reduce the visual impact. As the rehabilitation proceeded, periodic checks were made on its appearance from a distance so that adjustments could be made.

At the conclusion of this work on 24 January 1997 a satisfactory mimic of the natural form and texture of the slope had been achieved. However, marked differences between the colours of the surface sediment and exposed subsurface sediments precluded immediate satisfactory visual restoration, the colour contrast between the weathered natural surface and the disturbed subsurface diatomite being very high (up to four Munsell value units) (Fig. 3c). Differences in colour between surface and subsurface glacial clasts contributed to the visual contrast after rehabilitation. However, while this site remained visually evident when viewed from close up, it was less conspicuous from a distance of more than ~200 m because the colour was reasonably similar to that of natural swales that occur locally down the face of the scarp.

When monitored on 11 December 2000 the trench site was superficially indistinguishable from its appearance prior to excavation (Fig. 3d). There was no evidence of any slumping or downslope flow, suggesting that construction of the subsurface rehabilitation was adequate. Nor was there any evidence of lateral subsidence that might be attributable to melting of ground ice, nor of any discharge of fine material or salts onto the surface. This suggests the thickness and thermal characteristics of the deliberately re-consolidated infill provided a reasonable mimic of the original active layer. The small volume of fine subsurface dust that discoloured the ground surface immediately after initial rehabilitation was no longer evident, presumably having weathered or been removed by the wind, the latter implying diffuse contamination downwind. The scatter of small calibre gravel applied to the surface during rehabilitation could not be differentiated from the natural material to either side of the disturbed area. An equally satisfactory result was obtained after rehabilitation of an associated soil pit at the crest of the scarp (Table 2, site 4).

Figure 3. Marine Plain scarp trench (site 3); (a) prior to excavation; (b) during excavation, with structural rehabilitation of top section initiated.

Figure 3a.

Figure 3b.

Figure 3 continued. Marine Plain scarp trench (site 3); (c) immediately after rehabilitation immediately after rehabilitation in January 1997; and (d) and in December 2000.

Figure 3c.

Figure 3d.

Heidemann Bay

Heidemann Bay penetrates ~2 km into the lower part of Heidemann Valley (Fig. 1). The undulating valley floor is generally below 10 m altitude and is mantled by glacial sediment including many large surface boulders. Old un-rehabilitated soil pits at two locations showed negligible natural recovery between March 1997 and December 2000 (Table 2, sites 5 and 6). The research undertaken in 1997 involved re-use by a heavy excavator and other vehicles of an old, previously un-rehabilitated lightly bulldozed track (Table 2, site 7) and beyond this a short cross-country route (site 8), to facilitate excavation of a large trench (site 9).

The original proposal involved excavation right across the head of the Bay to allow assessment of the extent and continuity of the key deposits. However, this trench would have been ~500 m long, 4-6 m deep and 3-4 m wide, entailing a significant environmental impact. Prior to our departure for Antarctica a more environmentally appropriate compromise was reached involving a much shorter trench of ~50 m length, with provision for four smaller pits if needed. This was approved by the Australian Antarctic Division and relevant Minister following an environmental assessment that included public input and attempts to elicit responses from environmental groups. A decision was subsequently made in the field to reduce the size of the excavation even further to a single trench 20 m long. This still permitted the original scientific objectives to be achieved.

The precise site selected was on a stretch of raised gravelly beach superimposed upon the glacial sediments. This was chosen because it would not be necessary to remove large surface boulders that would be difficult to replace without their disturbance being evident and even greater impacts being generated in shifting them. This site was also selected because the adjacent areas already bore visible artificial impacts, primarily vehicle tracks across the valley floor, and a large stone quarry 200m east of the beach on the valley edge.

The trench was dug using an excavator with a 5.5 m arm. Snow cover reduced ground impact on the access route, which was also selected to avoid large boulders. To minimise ground disturbance while the digging proceeded, the uppermost material removed was used to construct a pad on which the excavator was positioned. The final trench measured 20 m long, ~2-3 m wide and 4.0-4.5 m deep. The width was kept to a minimum and reflects essentially the width of the bucket (plus about 0.5 m). The excavator was left at the site for the duration of the work to minimise the number of passes along the access route, to create additional shelter from the wind, and to form part of a barrier that was constructed to prevent wildlife falling into the trench while it was unattended. About 300 m^3 of sediment was removed and stored on the upwind side of the hole to maximise trapping back into the pit of any sediment blown from the heap. Even when great care is taken during excavations, fines from dry soils can be distributed by the wind and a large area become contaminated (Campbell and Claridge 1987) but the melting of recent light snow and the damp environment on the coast reduced this hazard considerably. Once the permafrost table was reached the melting of ground ice helped further dampen and stabilise the spoil, and there was little wind at the time of the excavation.

Examination, recording and sampling of the sediments was accomplished in 1.5 days. The operation was a race against melting of the permafrost and consequent loss of trench wall stability, and also against the weather, a major factor in planning and executing any proposed activity in Antarctica. Minor slumping due to permafrost melting was evident by the evening on which documentation and sampling was completed, and had worsened slightly by the next morning, with the risk of environmental damage increasing the longer the trench was kept open. Because rehabilitation would also have been made much more difficult had the trench become filled by snow it was re-filled immediately, despite a gathering blizzard with rising

Figure 4. Heidemann Bay trench (site 9) (a) during rehabilitation under blizzard conditions; (b) linear depression formed in rehabilitated surface between March 1997 and December 2000.

Figure 4a.

Figure 4b.

winds of 40-45 knots and blowing snow (Fig. 4a). This might have posed the risk of sediment being blown considerable distances had the moist condition of the spoil not by now become even more pronounced due to continued permafrost melting. The position of the trench and direction of the wind meant that any dust generated would be carried into the sea rather than contaminate soil surfaces, but after re-filling there was no evidence of dust on the snow any further than 5 m downwind. The excavator was used to compact the fill and to rake the surface. The sediment fitted back in the hole with negligible surface mound remaining, a result attributed to some mass loss having occurred through melting of ground ice.

No work was undertaken the next day as the blizzard continued. The following day was devoted entirely to rehabilitation, initially involving work with the excavator, which was then driven from the site, again with the ground impact reduced by a layer of new snow. Manual rehabilitation of the ground surface using spades, mattocks and rakes initially involved digging snow out of ruts made by the excavator so that these could be smoothed. This snow was later scattered across the rehabilitated area to maximise the available soil moisture and enhance the potential for frost heaving. This work was made much easier by the fact that insufficient time had elapsed to allow the disturbed ground to compact and harden. Care was taken to avoid smoothing the ground to such an extent that the rehabilitated surface appeared flatter and smoother than the natural surface surrounding it. Some retained glacial rocks were scattered back across the site with their weathered upper surface uppermost. Efforts were made to smooth the transition between disturbed and undisturbed ground to soften the contrast in colour and texture. These same procedures were employed along the full length of the access route (sites 7 and 8). The impact of two passes by the excavator proved visually less than that caused by several traverses by a four wheel drive vehicle used to carry other equipment and heavy materials to the site. The hand-tool phase of the rehabilitation process took ~2.5 person days.

At the conclusion of the rehabilitation work on 8 March 1997 an acceptable mimic of the form and texture of the original surface had been achieved. The colour contrast between disturbed and undisturbed sediment matrix was low to moderate at 1-2 Munsell value units. Rock colour comparisons also revealed only moderate contrast at two Munsell value units. The remaining visual impact varied according to the distance from which the site was viewed. The colour contrast proved relatively inevident from close up where there was no immediately juxtaposed undisturbed and disturbed ground, a minor contrast was more evident from a slightly greater distance, but from beyond ~100 m distance it was difficult to discern. We were encouraged that when we photographed the rehabilitation from the air a week later a helicopter pilot who had previously overflown the trench repeatedly at low altitude was unable to identify where it had been.

When monitored on 14 December 2000 the trench site could not be located visually on the ground without using photographs. Once the target area had been located accurately a slightly darker colouration and slight relative scarcity of surface rocks was discerned where spoil had been stockpiled. A subtle linear depression a few centimetres across, less than 1 m long and up to 5 cm deep was found to have formed along the line of the trench and to have been partly filled by in-washed fine sediment (Fig. 4b). Though visually similar to nearby natural features, this depression may reflect either settling of the spoil or frost cracking, also conceivably triggered by the disturbance. Neither the trench site nor access route were readily discernible upon overflying the site at ~50 m altitude. That part of the older vehicular track that was re-used and rehabilitated in 1997 (site 7) was just discernible at ground level, but the precise location of the rehabilitated cross-country access route (site 8), traversed by the excavator, 4WD vehicles and pedestrians, could no longer be discerned (Figs 5a and 5b). The un-rehabilitated parts of the older bull-dozed track remained conspicuous.

Figure 5. Heidemann Bay cross-country access track (site 8); (a) before rehabilitation in March 1997; (b) in December 2000. The trench site (site 9) is immediately behind and to the right of the researcher.

Figure 5a.

Figure 5b.

DISCUSSION

These results demonstrate that long term impacts of ground disturbance can be minimised if maximum advantage is taken of the opportunities to review and modify procedures at each of the project design, environmental review, site selection, operational and rehabilitation phases. Careful planning, siting, management and rehabilitation of any excavation are important. Confining traffic to defined access routes, and where possible to snow covered ground rather than sediment surfaces, reduces potential damage to the ground. At Heidemann Bay the construction of a pad from which the excavator could work considerably reduced potential surface disturbance. At Marine Plain, minimising trampling of the soft diatomite in the first place proved much more effective than any rehabilitation afterwards. Care is required in stockpiling spoil, useful approaches include placing it on a sheet to prevent contamination of adjacent surfaces, or in a bag to prevent it being redistributed by the wind. The shape of the disturbance is also important. At Heidemann Bay the linear disturbance of the old bulldozed track was less easily rehabilitated than was the more irregularly-shaped disturbance at the trench site, even though the magnitude of the works at the latter was vastly greater.

Our evidence suggests that a better result is possible with immediate diligent rehabilitation than if rehabilitation occurs after a significant delay. Even the site of our main trench in the thermokarst at Marine Plain (site 3) appeared to have achieved a greater degree of stability, and was visually less evident, than some disturbances that were decades older but which had been subject to minimal or no rehabilitation.

We conclude that it is critical that rehabilitation is properly designed and programmed, and is executed immediately following disturbance. Rehabilitation must be viewed as an integral part of a project, not just an obligatory and token exercise achieved by merely shovelling a few spadefuls of spoil back into a hole. Rehabilitation can be aided by the availability of photographs of the site taken prior to disturbance.

The likely success of different rehabilitation strategies is highly dependent on site conditions. The long term impact of any artificially accelerated melting of permafrost appears strongly influenced by the degree to which the ice is segregated within the sediments and the nature of those sediments. Only limited segregation of ground ice was evident at Marine Plain but the acceleration of its melting by artificial disturbance of the active layer at the Big Ditch site (site 2) was nevertheless sufficient to trigger accelerated thermokarstic processes in the silty diatomite. In contrast, while a comparable degree of ice segregation was revealed in the Heidemann Bay trench we found no evidence of thermokarst processes affecting the poorly sorted glacial sediments.

Most of the colour contrast left after excavation derives from unweathered matrix material brought to the surface. Whereas raking proved a very satisfactory way to diffuse edge contrasts at Heidemann Bay where the colour contrast between surface and unearthed subsurface material was moderate, the strong colour contrast between the surface and subsurface material at Marine Plain meant that employment of the same technique there would have served only to broaden the area of visually obvious disturbance. Rock colours vary considerably due to differences in rock type, but subsurface rocks are commonly unweathered and coated by unweathered matrix material, hence the colours of mineral constituents are often not as dramaticlaly brought out as with surface rocks.

Regular and effective monitoring to allow assessment of the impacts of ongoing activities, the verification of predicted impacts and the early detection of unforseen effects are also important and are required under the Madrid Protocol (Lyons 1993). Monitoring also enables rehabilitation methods to be assessed and improved for the future. Respondents to the Heidemann Bay public consultation process stressed the need for long term monitoring. However, there must be an appropriate mechanism to ensure monitoring can occur. A formal monitoring process for disturbed sites is required, rather than opportunistic, ad hoc monitoring. In establishing a formal monitoring processes and setting rehabilitation and monitoring requirements, the relative roles of the proponent of the disturbance, and the management agency and its various staff, needs to be realistically appraised and taken into account. For effective monitoring to occur there must be both a commitment and resourcing. Monitoring must also be properly designed and programmed. It is generally beyond the capacity of individual scientists who may never be able to return to Antarctica. We were fortunate in being able to undertake monitoring ourselves in December 2000 while transiting through Davis, but the circumstances that permitted this were uncommon. While our proposal for monitoring of the 1997 excavation was endorsed by the agency responsible for management of the area, up until December 2000 no monitoring had occurred. Presumably the agency either did not have the resources to conduct the monitoring or had not considered it a priority, even though the Heidemann Bay trench was probably the largest research excavation ever undertaken in East Antarctica.

Monitoring should employ objective criteria such as soil colour charts which provide an effective means of measuring visual impact, and careful photo-monitoring. Monitoring techniques must not themselves create an additional environmental risk or impact. Documentation of the rehabilitation and monitoring results is also critical for ongoing monitoring and assessment. An adequate database on disturbances and rehabilitation measures is essential. Our capacity to evaluate recovery of sites disturbed prior to 1997 was seriously impeded by the lack of reliable information concerning the age, location, dimensions and any rehabilitation history of earlier excavations.

CONCLUSIONS

The case studies presented here demonstrate the value of careful, planned, expeditious and monitored rehabilitation of disturbed sites in Antarctica, a highly sensitive environment that is deserving of the most stringent environmental protection and care. The relatively small disturbances reported here also provide a potentially useful analogy for larger scale activity associated with the provision of infrastructure in Antarctic environments, such as the significant ground impacts associated with Australia's Antarctic bases. A legacy of past disturbance exists in Antarctica, not all present-day activities are environmentally benign, and pressures on the Antarctic environment may well increase in future. An unsuccessful 1988 proposal to establish a centre in the Vestfold Hills to cater for up to 16,000 tourists a year hints at future possibilities (Martin 1996:257). Developing a higher level of expertise and experience in Antarctic land surface rehabilitation is warranted.

ACKNOWLEDGMENTS

The monitoring was made possible by an Antarctic Science Grant and other assistance from the Australian Antarctic Division. We very gratefully acknowledge the contribution of Sel Peacock whose skill in operating the excavator and attention to detail during the original work at Heidemann Bay was outstanding. Peter Corcoran, Pene Greet, Melissa Giese, Steve Richards, Sarah Mills and Noel Ward provided assistance in the field. Eric Colhoun, Mick Brown and Bruce Chetwynd commented on earlier drafts.

REFERENCES

Antarctic Treaty Consultative Parties (1992). *Protocol on Environmental Protection to the Antarctic Treaty - Final Report of the Eleventh Antarctic Treaty Special Consultative Meeting, Madrid, 22-30 April 1991; 17-22 June 1991; 3-4 October 1991.* (Ministerio de Asuntos Exteriores: Madrid).

Burgess, J.S., Spate, A.P. & Norman, F.I. (1992). Environmental impacts of station development in the Larsemann Hills, Princess Elizabeth Land, Antarctica. *Journal of Environmental Management* **36,** 287-299.

Campbell, I.B., Balks, M.R. and Claridge, G.C.C. (1993). A simple visual technique for estimating the impact of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record* **29** (171) 321-328.

Campbell, I.B. and Claridge, G.G.C. (1982). The influence of moisture on the development of soils of the cold deserts of Antarctica. *Geoderma* **28**, 221-238.

Campbell, I.B. and Claridge, G.G.C. (1987). '*Antarctica, Soils, Weathering Processes and Environment'.* (Elsevier: Amsterdam).

Claridge, G.G.C., Campbell, I.B., Powell, H.K.J., Amin, Z.H. and Balks, M.R. (1995). Heavy metal contamination in some soils of the McMurdo Sound region, Antarctica. *Antarctic Science* **7**(1), 9-14.

French, H.M. 1976. '*The Periglacial Environment'.* (Longman: London).

Goddard, E.N., Trask, P.D., De Ford, R.F., Rove, O.N., Singlewald, J.T.Jr. and Overbeck, R.M. (1948). *Rock Colour Chart.* Geological Society of America: Boulder, Colorado).

Graham, A. (1997). Antarctic policy review. *The Tasmanian Conservationist* **256**, 22-23.

Hirvas, H., Nenonen, K and Quilty, P. (1993). Till stratigraphy and glacial history of the Vestfold Hills area, East Antarctica. *Quaternary International* **18**, 81-95.

Kiernan, K and McConnell, A. (2001). Impacts of geoscience research on the physical environment of the Vestfold Hills, Antarctica. *Australian Journal of Earth Sciences* **48**, 767-776.

Kiernan, K., McConnell, A. & Colhoun, E. (1999). Thermokarst landforms and processes at Marine Plain, Princess Elizabeth Land, East Antarctica. *INQUA XV International Congress, 3-11 August 1999, Durban, South Africa. Book of Abstracts*, 98.

Laurie, M. (1975). '*An Introduction to Landscape Architecture'.* (Elsevier: New York).

Lyons, D. (1993). Environmental impact assessment in Antarctica under the Protocol on Environmental Protection. *Polar Record* **29**(169), 111-120.

McVee, C.V. (1973). Permafrost considerations in land use planning. In 'Permafrost. North American Contribution to Second International Conference' pp. 146-151. (National Academy of Sciences, Washington DC).

Martin, S. (1996). '*A History of Antarctica'.* (State Library of NSW Press: Sydney).

Parker, B.C. and Howard, R.V. (1977). The first environmental impact monitoring and assessment in Antarctica. The Dry Valley Drilling Project. *Biological Conservation* **12**, 163-177.

Schofield, E. (1972). Presenting the scientific value of cold desert ecosystems: Past and present practices and a rationale for the future. In *Conservation problems in Antarctica* (Ed. B.C. Parker) pp. 193-227 (Virginia Polytechnical Institute, Blacksburg, Virginia).

United States Forest Service (1974). *National Forest Landscape Management Volume 1,* Agriculture Handbook **434** (United States Forest Service: Washington DC).